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MEASUREMENT OF SIMULATED DROP SIZE DISTRIBUTION WITH AN OPTICAL SPECTRO PLUVIOMETER: SAMPLE SIZE CONSIDERATIONS

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ABSTRACT

Knowledge of drop size distributions is important for deriving various rain erosivity parameters. This study investigates the potential of an optical spectro pluviometer (OSP) to measure drop size distributions. Particular attention is paid to the impact of drop sample size and derived erosivity parameters. An experimental set-up using a rainfall simulator and an OSP is described. The OSP allows a continuous real-time sampling of the drops. Results on drop size distributions and sampling effects are discussed. A simulation aimed at reproducing the sampling made with the widely used flour-pellet or filter-paper method is described. From this simulation, recommendations on the sample size of the collected drops needed for an accurate determination of median drop size and kinetic energy are given. Past studies reporting drop size characteristics have often used too small a sample for an adequate description of rain erosivity. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: drop size distribution; sample size; rain simulation; optical spectro pluviometer

INTRODUCTION

Over the last decades, a large number of studies aimed at measuring rain drop size distributions (DSD) at the ground have been conducted for two basics reasons: (i) for assessing rain erosivity (e.g. Bubenzer and Jones, 1971; Gilley and Finkner, 1985; McIsaac, 1990); or (ii) for quantifying the rain intensity from radar measurements (e.g. Stout and Mueller, 1968; Battan, 1977; Sauvageot, 1988). A large number of methods have been developed to measure DSD. The two most widely used methods are the filter-paper method, first introduced by Wiesner (1895), and the flour-pellet method first reported by Bentley (1904) (e.g. Hall, 1970; Carter *et al.*, 1974; Park *et al.*, 1983; Cerdà, 1997; Erpul *et al.*, 1998).

The great advantages of such methods are their simplicity and their exportability to the field without a large technical support. However, these methods have three main disadvantages: (i) data analysis is very time-consuming; (ii) in order to avoid overlapping (of the pellets or of the stains on the filter paper), drop samples are taken during very short time periods (equal to or less than 1 s), which means that DSD are estimated from non-continuous samples which contain a limited number of drops; and (iii) a consequence of the two first disadvantages is that these methods are not able to provide real-time measurements.

The lack of automatic recording and the time-consuming nature of these methods led to the development of new and more sophisticated techniques. Some of the recording devices that have been developed are based upon; (i) a direct photographic technique (Jones, 1956); (ii) the measurement of a force applied to a transducer during the drop impact (Joss and Waldwogel, 1967); (iii) measurement of the voltage produced by

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a drop striking the surface of a piezoelectric transducer (Imeson *et al.*, 1981); (iv) electroacoustic principles (De Wulf and Gabriels, 1980; Kinnel, 1972); or (v) the occultation of a light beam by falling drops (Knollenberg, 1970; Hauser *et al.*, 1984; Illingworth and Stevens, 1987).

The objective of this study was to investigate the possibilities of using an optical spectro pluviometer (OSP), which is based on optical shadowgraph principles (Klaus, 1976; Hauser *et al.*, 1984; Salles *et al.*, 1998), to assess DSD. Laboratory experiments using a downward-oriented, fixed-nozzle rain simulator and an improved OSP have allowed us to obtain a long period of continuous measurements of the DSD using different water pressures, discharges and nozzle types. After a description of the OSP and the experimental set-up we discuss in more detail the assessment of the parameters related to the DSD and the associated sampling uncertainties. Recommendations for the drop sample size are given in the last section.

MATERIALS AND METHODS

The two main components of the experimental set-up are the rainfall simulator and the OSP. Rainfall was simulated with a downward-oriented, single-nozzle, continuous-spray system (Poesen *et al.*, 1990). Tap water was pumped to the nozzle. The discharge and the pressure at the nozzle are regulated by valves located at the output of the pump. During each sampling period the water discharge and the pressure were controlled carefully. In order to allow comparisons with other rain simulators, the height of fall of the drops and the output discharge from the nozzle are the two preferential parameters (Borselli, 1998). The water pressure is also measured with a manometer in order to detect changes of the hydraulic equilibrium established at the beginning of the experiment.

The OSP used to measure the DSD was installed vertically below the nozzle (at 2·5 m height) in the centre of the sprinkled area. The OSP was designed to measure the size and fall velocity of raindrops at the ground (Hauser *et al.*, 1984; Salles *et al.*, 1998). The principle of this shadowgraph instrument is simple. The infrared light (0·9 μm) transmitted by a diode illuminates a 60 cm^3 cuboid beam of parallel light shaped by a pair of converging lenses and rectangular masks. The total light intensity transmitted through the beam is monitored by a single receiving photodiode, which delivers an electric signal proportional to the received light intensity. When a drop falls across the beam, the light intensity received by the photodiode decreases. The amplitude and the duration of the signal variation are proportional, respectively, to the cross-section of the drop and to its residence time in the beam. The residence time can be converted to a fall velocity assuming the drop crosses the two horizontal faces of the beam separated by the known height of 1 cm. A modern digital acquisition processor implemented on a microcomputer allows simultaneous sampling and real-time processing of the signal. For each drop, the diameter (corrected for the oblate ellipsoid effect, according to Pruppacher and Pitter, 1971), the residence time and the arrival time (time at which the drop enters the beam) are computed and archived on a hard disk. The measured drop diameter range is 0·3 to 4·7 mm. Raindrops with diameter greater than 4·7 mm are all classified in the upper class: 4·8–5·0 mm. The residence time range is between 1 and 40 ms (thus the velocity range is 0·3 to 10 m s^{-1}). From the two drop characteristics (diameter and velocity) the OSP allows real-time computation of the DSD and derived parameters (e.g. kinetic energy, momentum).

The data stored on the hard disk are also used in real time to estimate the DSD expressed in percentage of volume of water. A 24-step histogram of the percentage of rain volume in 24 classes of drop diameter (class width is equal to 0·20 mm) is plotted on the computer screen at the end of each minute of sampling. A histogram giving the distribution of the fall velocity versus the diameter is also displayed on the screen.

The capacity of the acquisition system to capture high drop flux was established during a preliminary experiment. The software samples the drops on a time basis of 1 min and displays the DSD at the end of the minute. The sampling is continuous. The maximum number of drops that could be sampled and processed during the 1 min period was tested to be near 5500. The sampling surface was reduced in such a way that the number of drops stayed below this value. For our experiments the sampling surface was 4 cm wide and 6 cm long (24 cm^2).

As suggested by Brandt (1989), the drop diameter at which half the sample (by volume) is composed of larger drops and half of smaller drops, the so-called D_{50} (the median volume drop diameter), is the parameter

Table I. Experimental conditions during the acquisition of the three drop datasets. I is the mean rain intensity measured with three pluviometers. D_{50} is the median volume drop diameter. KE_{eq} and M_{eq} are, respectively, the equivalent kinetic energy and the equivalent momentum derived from the OSP measurement. The height of fall was 2·5 m

Dataset	Nozzle	Discharge ($\mathrm{l\ min^{-1}}$)	Pressure (bar)	I ($\mathrm{mm\ h^{-1}}$)	Sampling duration (min)	D_{50} (mm)	KE_{eq} ($\mathrm{J\ m^{-2}\ mm^{-1}}$)	M_{eq} ($\mathrm{kg\ m\ s^{-1}\ m^{-2}\ mm^{-1}}$)
1	460·788	2·8	0·21	38	50	1·47	18·0	5·7
2	461·008	9·5	0·36	108	110	2·41	27·4	7·2
3	461·008	11·8	0·55	106	50	1·92	23·3	6·5

chosen to characterize the DSD. The second rain parameter, which in most erosion models is representative of the eroding power of the rainfall, is the equivalent kinetic energy (KE_{eq}) (e.g. Poesen, 1985; Morgan *et al*, 1998). KE_{eq} is computed from the sum of the kinetic energy (ke) of each individual drop:

$$ke = \rho \pi D^3 / 12 V_t^2(D)$$

where D is the drop diameter measured by the OSP, $V_t(D)$ is the terminal fall velocity of a drop with diameter D derived from Beard (1976) assuming standard atmospheric conditions (20°C and $1{\cdot}013 \times 10^5$ Pa), and ρ is the density of water in standard conditions.

The third parameter, the momentum of the rain (M_{eq}), which is also suggested as a good rain erosivity index to describe splash erosion (e.g. Rose, 1960; Park *et al.*, 1983; Styczen and Høgh-Schmidt, 1988) is determined from the sum of the momentum (m) of each individual drop.

$$m = \rho \pi D^3 / 6 V_t(D)$$

Experiments using the rainfall simulator and the OSP have allowed us to measure the rainfall characteristics continuously during periods of 1 h or more. The advantages of the use of simulated rainfall are the control over the rain intensity through the nozzle discharge and pressure, and the fact that negative environmental conditions for the OSP measurements (Salles *et al.*, 1998), especially windy conditions, are avoided.

For each experiment the measurement procedure was as follows: fixing the value of the water discharge at the nozzle outlet by regulating the valve. The discharge was measured over 2 min at the beginning and at the end of a 1 h period during which raindrops were sampled with the OSP. The two discharge measurements were made in order to control the stability of the discharge over time. Following this procedure, three datasets have been selected (two rain periods with duration of 50 min and one with duration of 110 min).

RESULTS AND DISCUSSION

Drop size characteristics for different nozzles

Two nozzles have been used during the experiment. A first set of data obtained with a nozzle also used by Poesen *et al*. (1990) (a Lechler full-cone nozzle numbered 460·788 with an operating discharge of 2·8 $\mathrm{l\ s^{-1}}$ and an operating pressure of 0·21 bar) was recorded during a period of 50 min. The two subsequent datasets have been obtained by using a Lechler full-cone nozzle numbered 461·008. These two datasets were collected over 110 and 50 min with operating discharges of 9·5 and 11·8 $\mathrm{l\ s^{-1}}$ and operating pressures of 0·36 and 0·55 bar, respectively. Experimental conditions and DSD characteristics measured with the OSP are reported in Table I.

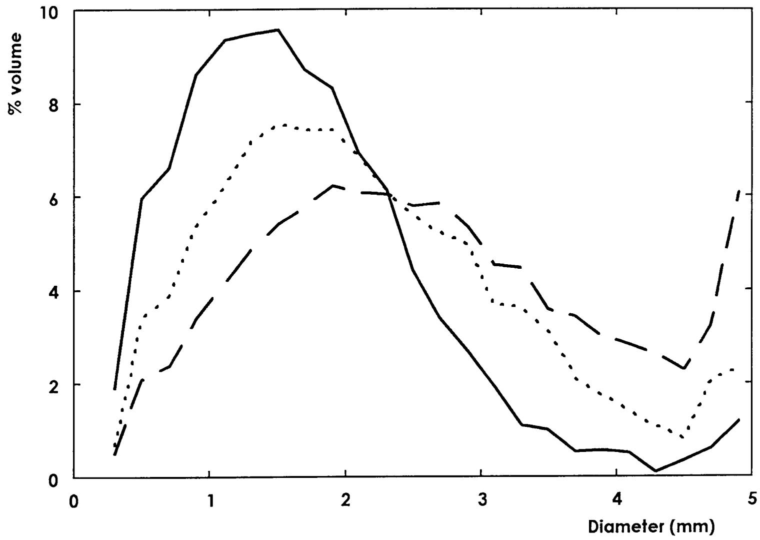

Figure 1. Drop size distributions (DSD) measured by the OSP for a 460·788 nozzle (bold line) and for a 461·008 nozzle operating at a discharge and pressure of, respectively, 9·5 l s^{-1} and 0·36 bar (dashed line) and 11·8 l s^{-1} and 0·55 bar (dotted line)

From these three datasets, DSD related to the volume percentage have been derived and plotted in Figure 1. Numerical values for three erosivity parameters of interest, i.e. M_{eq}, KE_{eq} and D_{50}, are reported in Table I. The rainfall intensity has been measured by exposing three rain gauges at the same position as the OSP for 20 min.

A relatively important volume percentage is observed for the last drop diameter class (i.e. 4·8–5·0 mm) on the three DSD graphs. In fact, this diameter class includes all the drops with a diameter larger than 4·7 mm. Therefore, the high volume percentage value is due to a class width that is actually larger than the width of the other classes. We have also to consider that the DSD is expressed in volume percentage. Only one drop with a diameter equal to 4·9 mm is needed to give the same volume as 15 drops with a diameter of 2·0 mm.

The first nozzle (460·788) produced a rain intensity equal to 38 mm h^{-1} (Table I). Most of the contributed water comes from the drop range diameter between 1 and 2 mm (Figure 1). Rain intensity from the second nozzle (461·008) is higher: 107 mm h^{-1} in the centre of the sprinkled area. The DSD present wider spectra (Figure 1). The different shape of the DSD from samples 2 and 3 illustrates one of the pressure influences on the DSD. A pressure increase equal to 53 per cent induces a decrease of D_{50} from 2·41 to 1·92 mm (20 per cent) and a lesser decrease of KE_{eq} and M_{eq} respectively, of 15 per cent and 10 per cent. The second influence concerns the size of the sprinkled area which increases with the pressure and thus rain distribution and homogeneity over the sprinkled area. This influence is not discussed here because the study does not involve the effect of the spatial variability of intensity and DSD under the nozzle.

The same rainfall simulator has been calibrated by Poesen *et al.* (1990) and by Borselli (1998). In both studies DSD was measured by the filter-paper method. Numerical values of D_{50} obtained by these authors are reported Table II. Considering the different methods used, the slightly different operative parameters of the nozzle and especially the sample size effect, discussed later, D_{50} values obtained by Poesen and Borselli are in agreement with the values measured with the OSP.

Sample size considerations

Except for the method used, the main difference between our data and those collected by Poesen *et al.* (1990) and Borselli (1998) comes from the size of the sample used to compute DSD.

Borselli (1998) estimated the DSD from a sample containing around 660 drops; the sample used by Poesen *et al.* (1990) consisted of less than 800 drops. With the OSP we sampled 125 547, 372 913 and 214 841 drops for the three datasets, respectively. There is no doubt that these are oversampling conditions, and the time

Table II. Values of the median volume drop diameter D_{50} measured by Poesen et al. (1990) and Borselli (1998) by the filter paper method for the same rainfall simulator and similar experimental conditions

Ref.	Nozzle	Pressure (bar)	Discharge (l min^{-1})	I (mm h^{-1})	D_{50} mm
Poesen *et al.* 1990)	460·788	0·206	NA	36·4	2·0
Borselli (1998)	461·008	0·54	12·3	67	2·25
	460·788	0·29	3·55	29	0·8

NA, not available

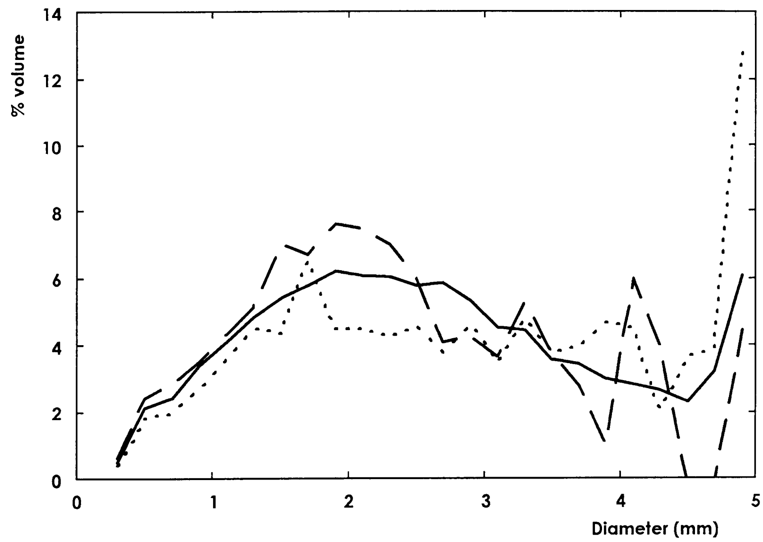

Figure 2. DSD sampled on a time basis of 1 min illustrating the two extreme values of D_{50}, i.e. 2·17 mm sampled at $t = 46$ min (dotted line) and 2·81 mm sampled at $t = 24$ min (dashed line) in comparison with the average DSD deduced from the 110 min dataset (bold line; $D_{50} = 2{\cdot}41$ mm). All data are taken from dataset 2 (461·008, nozzle operating at 9·5 l s^{-1} discharge and 0·36 bar pressure)

durations of the sampling (i.e. 50 or 110 min; Table I) are fairly long. These datasets have been collected with the objective of evaluating the sample size effect and the uncertainties induced.

Let us consider the largest drop sample, i.e. dataset 2 which was collected over 110 min with the 461·008 nozzle. In its original form the software of the OSP has been developed to measure DSD on a time basis equal to 1 min. Subdividing dataset 2 into 1 min intervals gives 110 samples and the 110 associated values of KE_{eq} and D_{50}. Measured on this time basis the DSD and the parameters related to the DSD exhibit large fluctuations. As an illustration, Figure 2 gives the extreme DSD computed on a sample basis of 1 min.

Therefore, if we consider samples measured over a time interval equal to 1 min this corresponds to a sample size of about 3400 drops. For the same population the kinetic energy fluctuates between 25·6 and 29·7 J m^{-2} m^{-1}, the momentum varies from 6·8 to 7·5 kg m s^{-1} m^{-2} mm^{-1} and the variation of D_{50} is in the range 2·17 to 2·81 mm. Examples of the different DSD shapes are given in Figure 3. The first 50 1-min samples are plotted on this figure. From these plots the following observations can be made: despite the fact that all samples are coming from the same drop population, the DSD shapes could be quite different from one sample to another. The difference is more evident in the diameter range larger than 2 to 3 mm. The shape could be flat as in sample 17, near to symmetrical as in sample 29, with high fluctuation in the higher diameter class as in samples 16, 19 or 40, and could also be a good approximation of the average DSD as in sample 36 or 39.

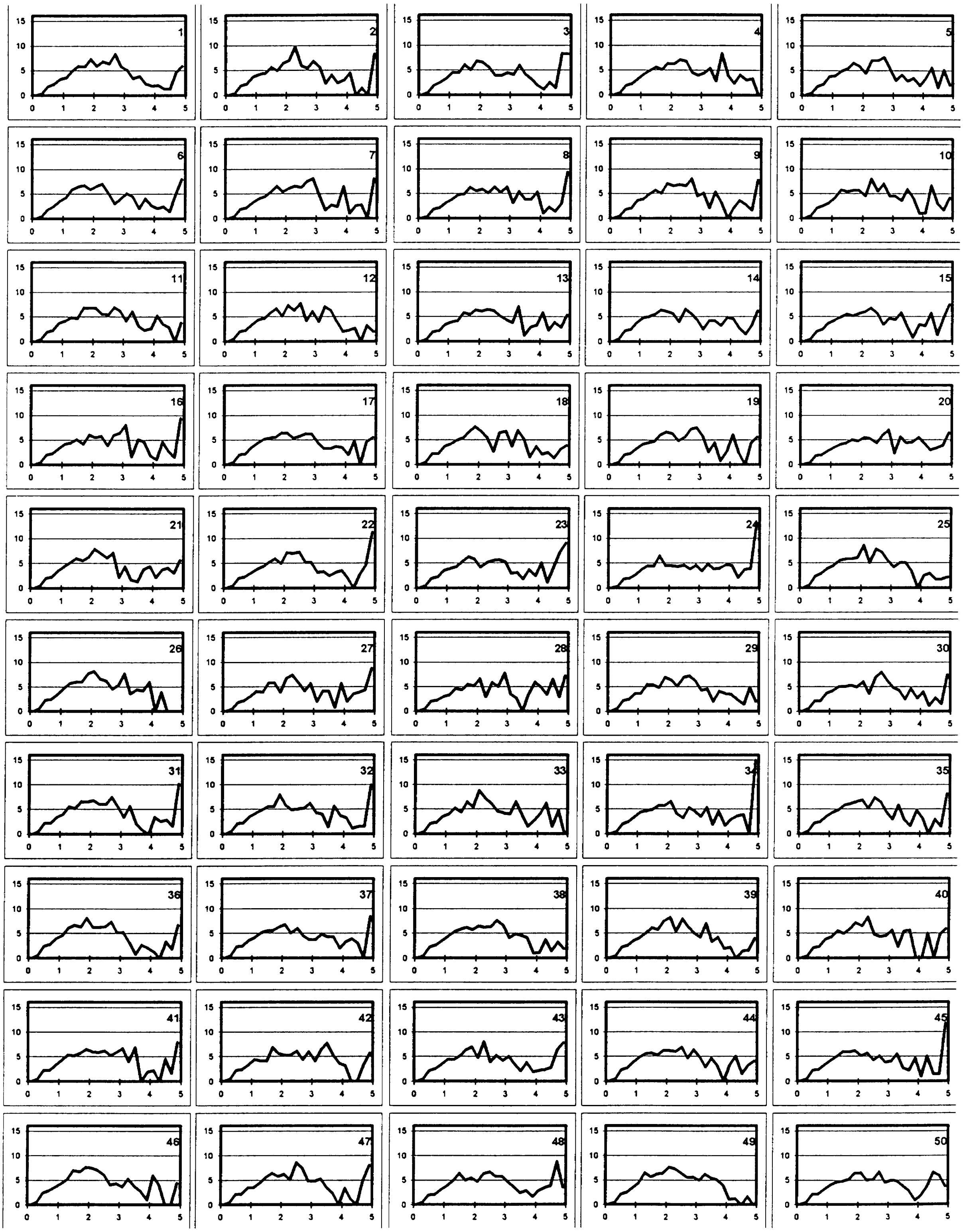

Figure 3. DSD measured with the OSP and the 461·008 nozzle at a pressure of 0·36 bar and a discharge of 9·5 l s^{-1}. DSD are derived on a time basis equal to 1 min. X-axes represent drop diameter (mm); Y-axes represent percentage of rain volume

By considering larger samples of 10 min duration, the DSD is the same as the DSD estimated from the complete 110 min dataset and the variation of the D_{50} parameter is less (between 2·33 and 2·45 mm); M_{eq} is in the range 6·8 to 7·0 kg m s^{-1} (m^2 mm^{-1}); and KE_{eq} remains between 25·8 and 26·6 J m^{-2} mm^{-1}.

In order to obtain a better understanding and a more precise description of the sampling effect, a simulation was made. It consists of reproducing the sampling from the more common filter-paper or the flour-pellet methods. These two methods sample, for a short period of time, drops that fall down onto the blotting paper or into the flour. The data stored during the sampling with the OSP are, for each drop, the arrival time at the ground, the diameter and the fall velocity. The simulation will randomly choose a first drop in the OSP sampled dataset and consider the next continuous N drops recorded. From these N drops the parameters related to the DSD will be derived. By repeating the random choice of the first drop in the original set and by varying the value of N we simulate the paper or flour sampling and observe the effect of the sample size (N) on the estimation of three rain parameters: KE_{eq}, M_{eq} and D_{50}.

The procedure has been repeated 100 times for each value of N between 100 and 200 000 drops. The data used for the simulation are from dataset 2 obtained with the OSP. This sample consists of 372 913 drops.

Ranges of the parameters estimated from simulated samples are plotted against sample size in Figure 4. Whatever the size of the sample, the average value of all samples with the same size from the simulation is close to the value deduced from the entire dataset. The lowering of the values of the mean parameters when the sample size decreases is in agreement with the simulation results of Smith *et al*. (1993). The main observation remains the variation of the three estimated parameters with sample size. The range of variation of D_{50} for the smaller samples is near the measurement range of the OSP. This range of variation decreases with an increase of the sample size. For samples with less than 10 000 drops, the D_{50}, M_{eq} and KE_{eq} are subject to significant fluctuations.

In order to quantify the accuracy of the estimation of the three parameters, we have plotted in Figure 5 the ratio between standard deviation and mean (coefficient of variation) versus the sample size. The results show that if we want to determine a value of D_{50} and KE_{eq} with an accuracy which is 3 per cent or less, we have to consider samples with at least 10 000 drops.

Let us compare these observations with the drop sample size reported in the literature. Most of the DSD in the literature have been obtained by time-consuming methods. The time factor reduces the sample size and the amount of available data. In Table III we have listed details of the size of the samples used in the DSD estimation from different studies. Only studies where such details are described are reported here.

Most studies reported in Table III have been made by using the filter-paper or the flour-pellet method. The sample sizes are different among the various studies. The sample sizes are small when the methods are time-consuming and become larger when the methods used are based on automatic sampling, which from an experimental point of view is understandable.

The sample size observed evolves from a minimum value of 32 drops (natural rainfall) to a maximum of near 30 000 (natural rainfall but cumulative data over many events). There is a large difference between data obtained under natural rain and data obtained with simulated rain. In natural rain conditions the time variation is another source of fluctuation of the DSD. McIsaac (1990) considers that temporal variations of the DSD in natural conditions are much more important than DSD variations according to the geographic location.

In most cases the size of the sample considered is around 1000 drops. Therefore, according to the results of this study, the parameters derived from the DSD are determined with an uncertainty of at least 7 to 10 per cent. We have also to keep in mind that our dataset has been obtained in idealized conditions: constant water pressure and discharge and sampling at a fixed location inside the sprinkled area. In natural rain conditions the variation of DSD will be higher. Gertzman and Atlas (1977), assuming a Marshall and Palmer (1948) drop size distribution, produced curves which permit the estimation of the coefficient of variation of rain parameters. A natural rain with DSD such that the median volume diameter is the same as the one of dataset 2 (D_{50} = 2·4 mm), sampled during 1 s with a sampling area of 1000 cm^2, will provide a coefficient of variation KE equal to 11 per cent.

Very few authors used large drop samples and were therefore unable to discuss the sample size effect. Panini *et al*. (1993) calibrated a rain simulator by the flour-pellet method. They concluded that a sample is representative of the population only if the number of collected drops exceeds 4000 to 5000. Their

(a)

(b)

(c)

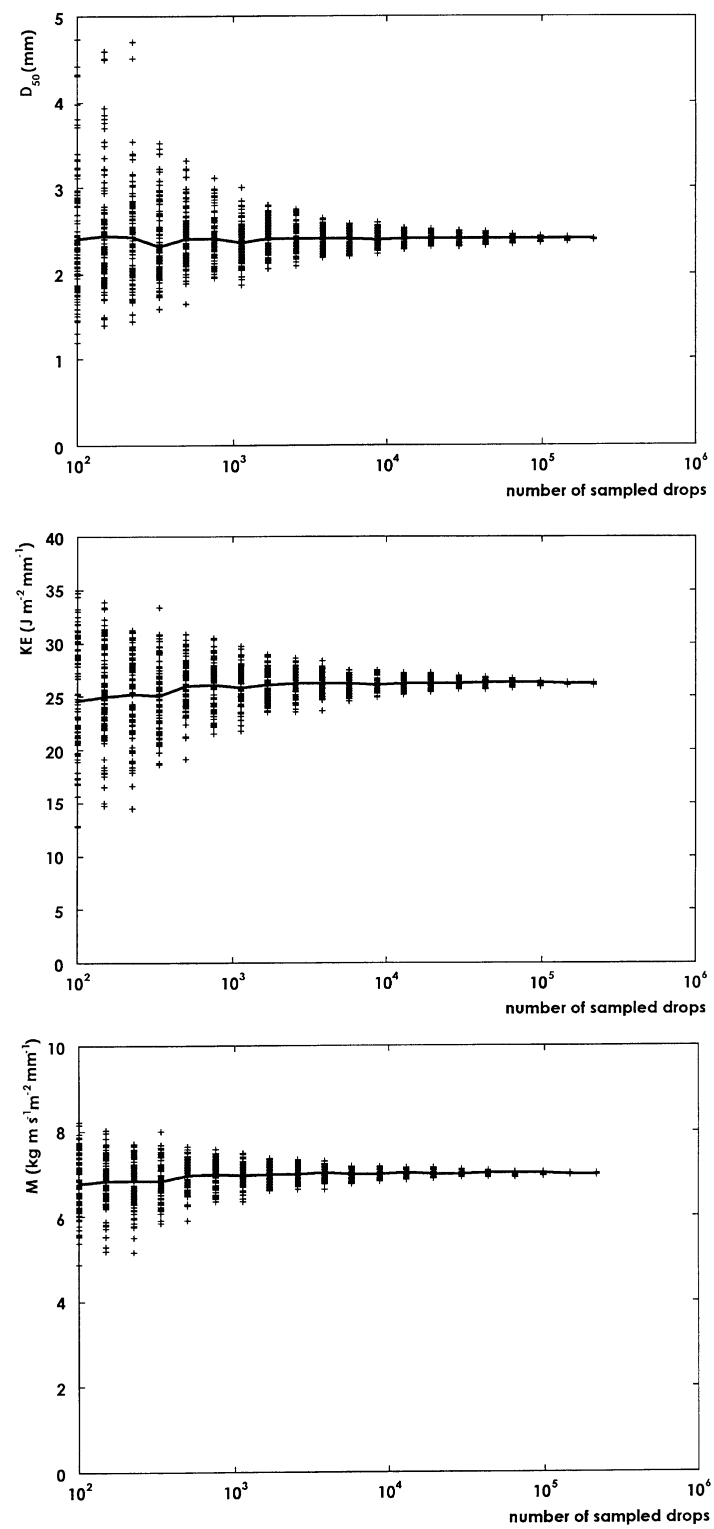

Figure 4. Estimated values of D_{50} (a), KE_{eq} (b) and M_{eq} (c) versus the number of sampled drops. Solid line represents mean. Results obtained from simulated sampling

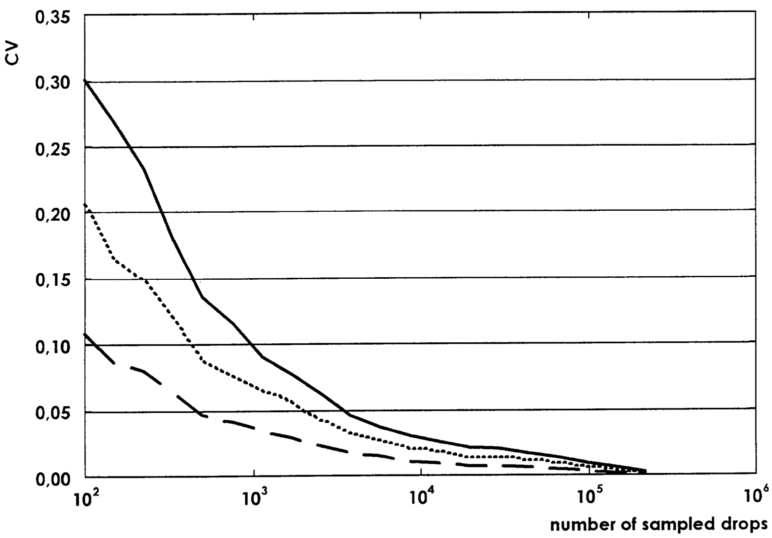

Figure 5. Coefficient of variation (CV) of the estimated value of D_{50} (solid line), M_{eq} (dashed line) and KE_{eq} (dotted line) versus the number of sampled drops

Table III. Description of the sampling conditions in different studies where DSD have been measured

Number of sampled drops	Measurement method	Type of rainfall	Rainfall intensity (mm h^{-1})	Reference
32–815†	Filter paper	Natural	1–120	Cerda (1997)
130–2525	Filter paper	Natural	0·5–25	Renard (1983)
158–193	Filter paper	Under vegetation	NA	Brandt (1989)
205	Raindrop camera	Natural	NA	Smith (1982)
247	Filter paper	Simulated	100	Rouhipour (1997)
452	Filter paper	Natural	NA	Lovejoy and Schertzer (1990)
500–1000	Filter paper	Natural	0·3–39	Bollinne *et al.* (1984)
527–8458	Optical disdrometer	Under vegetation	78·3	Hall and Calder (1993)
696	Joss and Waldwogel disdrometer	Natural	3·8	Waldvogel (1974)†
612			8·1	
960–12 280	Piezoelectric method		20-140†	Kowal and Kassam (1977)
965	Filter paper	Simulated	40	Govers *et al.* (1987)
1000–10 000	Flour pellets	Natural	1–200	Zanchi and Torri (1980) Torri (1998, pers. comm.)*
1638	Camera system	Natural	34	Jones (1992)
8855			3	
1125			1	
1228	Filter paper	Simulated	26	Bryan and Poesen (1989)
1404	Flour pellets	Natural	13·5	Laws and Parsons (1943)
2240	Oil method	Simulated	10–110	Zhao *et al.* (1996)
4000–5000	Flour pellets	Simulated	30–50	Panini *et al.* (1993)
4000–10 000	Laser optical method	Irrigation (sprinkler)	NA	Kincaid *et al.* (1997)
9985	Filter paper		78·3	Hassel and Richter (1988)
29 024	Filter paper		0–12	Best (1949)
13 996			0–4	
27 219			0–39	

NA, not available
* Sample size depending on tested intensity
†One minute samples

observations of the sample size vary between 500 and 6500 drops. In their study they did not quantify the error on the DSD and related parameters. Tuck *et al*. (1997) measured the size of droplets in agricultural sprays with a Doppler particle analyser and showed that approximately 12 000 to 14 000 droplets are needed to achieve an acceptable standard deviation of the median volume diameter.

Some authors present limitations on their sampling procedure. Bollinne *et al*. (1984) sampled natural rain with the filter-paper method. They arbitrarily rejected samples with a drop count of less than 200 and samples during which the rainfall intensity varied. Hudson (1961) sampled storms with the flour-pellet method and considered only samples that 'consisted of an adequate number of replication (usually nine)'. The Illinois State Water Survey rejected raindrop spectra samples containing less than eight drop images (Jones, 1992). Cerdà (1997), using the filter-paper method in natural rain, considered all samples whatever the size. He used sample sizes varying between 32 and 662 drops but with a wide range of rainfall intensity (from 1 to 120 mm h^{-1}).

Concerning the DSD shape, some authors identify bimodal distributions (e.g. Morgan, 1983). The bimodal aspect could be the result of an artefact of the simulator as shown by Morgan. In any case, DSD shapes and mathematical models used to describe DSD have to be selected with care and the sample has to be large enough to avoid sampling problems.

DSD are not commonly measured and in most studies empirical relationships between D_{50} and the rain intensity are used. These relationships have been obtained from DSD measurements. In these observations the variations due to sampling should be considered. The variation of D_{50} that we observe by simulating the sampling is in the same order as the variation of D_{50} versus the rain intensity. For example, Carter *et al*. (1974) published two scatter plots of D_{50} versus rain intensity, for rain intensities varying between 0 and 250 mm h^{-1}. These scatter plots have similar variation to those observed in Figure 4.

CONCLUSIONS

The accuracy of parameter estimation from DSD has been quantified using an OSP. It appears that in simulated conditions, with controlled discharge and pressure, a minimum sample size of 10 000 drops is required in order to estimate the DSD and the derived parameters such as D_{50}, M_{eq} and KE_{eq} with an accuracy of 3 per cent or less. These findings allow one to evaluate the accuracy of previously measured drop size distributions. The simulation results give an indication of the accuracy of the parameters estimated according to the number of drops sampled.

From the results we conclude that any sample smaller than 10 000 will yield a larger uncertainty. Future measurements of drop size characteristics should include at least 10 000 drops. However, given the DSD variation over time in field conditions, it is recommended to collect large drop samples at a time.

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